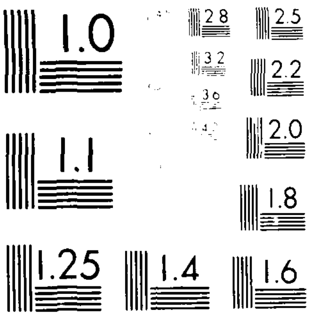
AD-A193 050 CRITICAL ISSUES AND DIRECTIONS FOR FRACTURE MECHANICS AND STRUCTURAL INTEGRITY(U) NAVAL RESEARCH LAB WASHINGTON DC M I JOLLES ET AL. 13 MAY 88 NRL-MR-6035 1/1

UNCLASSIFIED F/G 20/11 NL

END
DATE
FILMED
1-89
DTIC



MICROCOPY RESOLUTION TEST CHART

(2)

Naval Research Laboratory
Washington, DC 20375-5000

NRL Memorandum Report 6035

Critical Issues and Directions for Fracture Mechanics and Structural Integrity

M.I. JOLLES, P. MATIC, G.C. KIRBY III,
V.M. GENSHEIMER AND D.P. HARVEY II

Mechanics of Materials Branch
Material Science and Technology Division

May 13, 1988

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	UNCLASSIFIED
1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
3. DISTRIBUTION / AVAILABILITY OF REPORT	Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	NRL Memorandum Report 6035
5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION	Naval Research Laboratory
6b. OFFICE SYMBOL (If applicable)	Code 6382
6c. ADDRESS (City, State, and ZIP Code)	Washington, DC 20375-5000
7a. NAME OF MONITORING ORGANIZATION	
7b. ADDRESS (City, State, and ZIP Code)	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	Office of Naval Research
8b. OFFICE SYMBOL (If applicable)	
8c. ADDRESS (City, State, and ZIP Code)	Arlington, VA 22217
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO.	61153N22
PROJECT NO.	RR022-01-48
TASK NO.	
WORK UNIT ACCESSION NO.	DN480-509
11. TITLE (Include Security Classification)	Critical Issues and Directions for Fracture Mechanics and Structural Integrity
12. PERSONAL AUTHOR(S)	Jolles, Mitchell I., Matic, P., Kirby, George C. III, DeGiorgi, Virginia M. and Harvey, Daniel P. II
13a. TYPE OF REPORT	
13b. TIME COVERED	FROM TO
14. DATE OF REPORT (Year, Month, Day)	1988 May 13
15. PAGE COUNT	
16. SUPPLEMENTARY NOTATION	
17. COSATI CODES (FIELD, GROUP, SUB-GROUP)	
18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The development of concepts and methods suitable for the correct analysis of nonlinear inelastic material deformation and fracture is essential for applications of nonlinear fracture mechanics to questions of structural integrity and design. Recent results by the authors have addressed the integration of constitutive behavior and continuum damage concepts in the development of a consistent and versatile fracture mechanics methodology; formulation and solution of a constitutive representation; application of these ideas to analyses of initiation of defect propagation in complex material-structural systems subjected to monotonically increasing loads. The definition and application of a continuum stress-strain relation and a local continuum toughness results in the ability to scale from test specimen to structure. The formative concepts are reviewed and their application to relevant problems are investigated. Computational analyses coupled to experimental data from material test specimens are used to

(Continues)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS
21. ABSTRACT SECURITY CLASSIFICATION	UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL	Mitchell I. Jolles
22b. TELEPHONE (Include Area Code)	(202) 767-6451
22c. OFFICE SYMBOL	Code 6382

DD Form 1473, JUN 86 — Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

UNCLASSIFIED

19. ABSTRACT (CONTINUED)

determine the continuum material properties. Practical applications of the methodology are presented. The results indicate the concepts employed can provide a general approach for the analysis of relevant nonlinear fracture mechanics problems.

DD Form 1473, JUN 86

CONTENTS

A-1

CRITICAL ISSUES AND DIRECTIONS FOR FRACTURE MECHANICS AND STRUCTURAL INTEGRITY

INTRODUCTION

Fracture mechanics is the discipline in which concepts and methods are developed and applied for material selection and the assurance of structural integrity. The dimensional scale of interest in the study of fracture mechanics spans several orders of magnitude. It can, however, be divided into three distinct regimes: micromechanical, macromechanical and structural. The micromechanical scale is the domain where the mechanisms of deformation and damage may be described. The features of interest at this scale include dislocations, voids and microcracks. Constitutive relations in this domain are formed from hypotheses. The macromechanical scale relies on the concept of a homogeneous volume element which allows the continuous point determination of stress, strain and energy. A crack can be resolved to a dimension no smaller than the dimension of the volume element. The constitutive relations which describe the behavior in this domain are phenomenological. The structural scale, which is also considered to be continuous but may be globally inhomogeneous due to the nature of its design or fabrication, is on the order of structural component dimensions.

It is obvious that the features observed at one dimensional scale can only be used to describe and understand the behavior in a domain of equal or greater dimensional scale. It must be remembered that since an objective of the fracture mechanics discipline is to obtain solutions at the structural scale, any formulation must be able to accurately predict deformation and fracture at that scale.

Although significant work has been accomplished to describe the physical mechanisms at the micromechanical scale [1,2], it is difficult to realize its application for solution of deformation and fracture at the structural scale.

At the macromechanical scale, the classical concepts of fracture mechanics have been derived from global analyses of cracked bodies. This has resulted in the strain energy release rate [3], stress intensity factor [4], strain energy density factor [5] and contour integrals such as J [6]. These concepts are successful in predicting crack behavior when the loading is proportional (or periodic if crack extension due to fatigue is involved), the material exhibits moderate toughness and the constraint is high. These conditions result in local continuum deformations which approximate the restrictive hypotheses of the derivations. Since there exists a range of practical applications, and laboratory tests can be developed, which approximate these restrictions, classical fracture mechanics will remain a useful tool for the assessment of structural integrity.

Many problems, however, are significantly more sophisticated. These feature effects such as inelastic constitutive response, large deformations, non-proportional loading, non-self-similar crack extension or time-dependent behavior. These demand a more general approach than the classical fracture mechanics concepts based on a global energetic analysis of cracked bodies.

Manuscript approved October 18, 1987.

Previous work [7-9] has provided insight to conceptualize and implement a general continuum approach which uses the constitutive relations to describe deformation, damage and fracture by the continuous point variables of stress, strain and energy [10-18]. Then, for a structural analysis, given the geometry and boundary conditions of the problem, the constitutive relations are used in a computational solution (such as the finite element method) of the stress, stain and energy fields to assess the collective behavior of these variables. The critical points are determined and the load or time to fracture at a point is obtained from the local history of the stress, strain and energy.

CONCEPTS

Continuum Stress-Strain Relation

The rational development of a constitutive formulation which accurately quantifies the nonlinear behavior of solids is complex due to features such as triaxial deformation which is dissipative, path dependent and rate dependent; deformation which is sensitive to both dilatation and distortion; the coupling of mechanical and thermal response.

Physical assumptions which simplify the formulation do not necessarily reduce the problem to being trivial. Consider the assumptions of time-independent isothermal deformation. Further assume that the deformation is such that it is adequately described by the traditional flow rule of incremental plasticity which relates the components of stress and strain through an effective uniaxial stress and strain. The requirement, for these conditions, then becomes the determination of a material uniaxial stress versus strain relation.

Satisfying this requirement for inelastic behavior is not trivial. The round bar uniaxial tensile test specimen is typically used to obtain global load and displacement data. The data, for conditions of uniaxial homogeneous deformation, can be normalized to stress and strain. However, these conditions are approximated only for extremely small strains. Generally, the results of this data reduction are sensitive to test specimen geometry, as can be seen in Figure 1 for the engineering stress-strain responses of HY-100 steel. The true stress-strain responses will also exhibit geometry dependence. The deformation field is triaxial and inhomogeneous which precludes the simple algebraic reduction of the load and displacement data to stress and strain.

Determining the continuum stress-strain relation requires the uncoupling of the material and geometry influences of the observed test specimen deformation. This can be achieved by a hybrid computational-experimental analysis of the deformation of the test specimens. This has been done by testing a series of round bar tensile specimens with differing gage lengths and diameters; treating the continuum stress-strain relation as the unknown; performing finite element analyses of the extreme specimen geometries; iterating on the stress-strain relation until the differences between the predicted and observed specimen deformations are acceptably small.

The solution for the continuum stress-strain relation of HY-100 is shown in Figure 2. The predicted global and local deformations are compared with the experiments in Figures 3 and 4. The results indicate the ability to determine a unique stress-strain relation, for the assumptions discussed above, for which computational predictions of the deformation agree with experiments for different specimen geometries. Further details can be found in Reference [14].

Continuum Toughness

Consistent with the above discussions, a continuum definition of material toughness is embraced. Thermodynamic considerations require that the appropriate toughness parameter be a state variable relevant to the deformation process. This is particularly true when dissipative path-dependent material deformation and damage processes are occurring. Thus, the absorbed energy of a continuum material volume at fracture is defined as the material toughness.

The use of an energy density has distinct advantages for three-dimensional deformation and fracture. Energy density is a scalar which accounts for all components of the state tensors in a physically consistent manner.

In particular, for assumed time-independent isothermal conditions, this quantity is the strain energy density:

$$W = \lim_{\Delta V \to 0} \left[\frac{1}{\rho} \frac{\Delta W}{\Delta V} \right] = \int_0^{\epsilon} \frac{1}{\rho} \sigma_{ij} \, d \epsilon_{ij}$$

where ρ is the mass density. The material toughness is then:

$$W_c = \int_0^{\epsilon} \frac{1}{\rho} \sigma_{ij} \, d \epsilon_{ij}$$

where the subscript c represents the critical conditions.

For ductile materials which deform due to flow, under conditions where there are only small changes in the mass density, one may define a volume density of the strain energy:

$$W = \lim_{\Delta V \to 0} \left| \frac{\Delta W}{\Delta V} \right| = \int_0^{\epsilon} \sigma_{ij} \, d \epsilon_{ij}$$

with an associated material toughness:

$$W_c = \int_0^{\epsilon} \sigma_{ij} \, d \epsilon_{ij}$$

While the mass density of the energy is fundamental, the volume density is equally appropriate for assumed constant volume deformation processes.

For the case of a uniaxial stress-strain curve, corresponding to a one-dimensional state of deformation, the critical strain energy density corresponds to an area under the uniaxial stress-strain curve:

$$W_c = \int_0^{\epsilon} \sigma \, d \epsilon$$

This representation is desirable for use with traditional constitutive formulations which rely on an effective uniaxial stress-strain relation, as discussed previously. The termination points correspond to the points of observed failure of the test specimens used to determine the continuum stress-strain relation. The history of the triaxiality of the local deformation state at the center of the specimen and the resulting critical strain energy density are observed to depend on the specimen geometry, as can be seen in Figure 5 for HY-100. However, since the critical strain energy density is observed, for this material, to be relatively insensitive to the history of the deformation state, the value obtained from the tensile specimen which exhibits a triaxial deformation state from the onset of loading may be taken, for engineering purposes, as a material constant.

For a multiaxial state of stress, each of the six component stress-strain pairs must be evaluated and summed. While individual terms in the expression may be negative, their total must be positive.

Application of continuum toughness concepts provides the ability to predict the location as well as the load at continuum fracture. A priori assumption of the critical site is not required. A relative strain energy density ratio may be defined by normalizing the strain energy density at each point with respect to the critical strain energy density. As the load increases, deformation progresses until, at a location:

$$\frac{W}{W_c} = 1$$

and continuum fracture occurs.

Multilithic structures are assessed in a consistent manner. A critical value of the strain energy density will exist for each constituent material. The strain energy density at each point may then be normalized with respect to the appropriate constituent continuum toughness. When:

$$\left[\frac{W}{W_c} \right]_{n_c} = 1$$

and:

$$\left[\frac{W}{W_c} \right]_n < 1 \quad n = 1, \ldots, n_c - 1, n_c + 1, \ldots N$$

continuum fracture occurs in material n_c.

Relation Between Continuum and Micromechanical Features

Although one cannot predict the mechanisms of material deformation, damage and fracture from continuum concepts, there must be a consistency between observed continuum deformation and micromechanical features. It has been shown that the deformation of round bar tensile specimens of HY-100 steel is dependent on the interaction of continuum material properties and specimen geometry.

The fracture surface features of these specimens were examined using scanning electron microscopy. The results, shown in Table 1, indicate the geometry sensitivity of the proportions of failure due to cleavage, ductile tear, microvoid coalescence and the microvoid density and average aspect ratio. The mechanisms of material deformation and fracture are thus dependent on the geometry and loading and are not solely a material response.

STRUCTURAL INTEGRITY PREDICTIONS

Practical applications of the concepts to relevant problems of structural integrity are necessary. The problems addressed below are complicated by features such as component geometry, inhomogeneous material composition and nonuniform deformation fields. The local material properties, for each problem, were determined consistent with the concepts discussed above for each constituent material. A nonlinear finite element analysis was conducted for each problem using the ABAQUS code.

T-Section with Weld Defect Across Flange

Consider a butt welded T-section with a lack of fusion weld defect across the flange as shown in Figure 6. The critical location, that of the greatest relative strain energy density, determined from the analysis is shown in Figure 7. The strain energy density at that location versus applied load is also presented. The strain energy density reaches 4.09 ksi, the continuum toughness of the weld metal, at an applied load of 30.5 kips. Subsequent to the analysis, an experiment was conducted and the load at initiation of failure determined to be 32.0 kips. Examination of the fracture surface indicated that initiation occurred in the vicinity of the location as predicted. Further details can be found in Reference [13].

Relative Criticality of Defect

Consider a butt welded plate with a through thickness lack of fusion weld defect as shown in Figure 8. The analysis determines the relative strain energy density to be high at two locations, at the edge of the defect and at the weld to base metal fusion line. The strain energy density versus applied load at these locations are shown in Figure 9. The strain energy density at the defect edge initially rises rapidly. However, this trend is not maintained and the strain energy density at this location does not reach the continuum toughness of the weld metal. A priori assumption of the criticality of the defect leads to the conclusion that integrity is maintained. However, the deformation progresses and concentrates in the vicinity of the fusion line, as seen in Figure 10. It can be concluded that failure occurs when the strain energy density reaches the local continuum toughness of 4.09 ksi at an applied strain of 7.8%. Further details can be found in Reference [18].

Weld System Performance

The use of these concepts for the optimum design of material-structural systems can be demonstrated by considering the influence of weld metal properties and presence of weld crown on the integrity of HY-100 weld systems. Analyses were performed on butt welded plates with double V-welds, one inch thick and twenty inches in length, subjected to longitudinal tension as shown schematically in Figure 11. The heat affected zone was divided into four subzones for the purpose of assigning appropriate material properties. Candidate weld metals possessed yield strengths 17% over, even or 17% under matching the yield strength of the base metal. The strain energy density at each point is assessed relative to the continuum toughness of each constituent material to determine the location and load of failure initiation. The results, presented in Figure 12 in terms of the predicted global load-displacement behavior for each condition, indicate that the system ductility significantly depends on the weld metal properties and presence of the weld crown. Similar analyses can be conducted to assess the influence of other material, geometry and loading conditions. Further details can be found in Reference [16].

CLOSURE

The continuum stress-strain relation and the continuum toughness, in terms of a critical strain energy density, provide a method for the solution of sophisticated problems in the field of fracture mechanics. Features such as constitutive and geometric nonlinearities, inelastic deformation, triaxial non-proportional loading and multilithic structures pose no barriers to application of the method. The principles may be extended for time-dependent and non-isothermal analyses.

The continuum material properties are determined by a hybrid computational-experimental analysis of the deformation of simple uncracked laboratory test specimens. This allows the uncoupling of material and geometry influences of the observed test specimen deformation. This continuum stress-strain relation and continuum toughness are the basic continuum properties of the material for assumed time-independent isothermal conditions.

Observed micromechanical features are directly relatable to the continuum deformation. The mechanisms of material deformation and fracture are thus dependent on the geometry and loading and are not solely a material response.

The approach provides a methodology for the prediction of structural integrity. A priori assumption of the failure initiation site is not required, providing the ability to predict behavior for problems where the failure initiates away from an existing defect and for problems where no defect exists.

The future demands on the discipline of fracture mechanics will be complex and sophisticated. In addition to assessing the integrity of existing structures and material selection, fracture mechanics must provide a rational framework for the determination of design allowables, both structural and material. This will result in improved structural performance and provides the basis for the scientific design of new advanced material systems. This will allow the fulfillment of requirements of structural configurations in an optimum manner with respect to mission specifications, weight, damage tolerance, durability, survivability and reliability.

The demands are further complicated by the emphasis on multimission capability. This requires that structures are able to operate under radically different loading conditions. Future applications will necessitate materials, structures and operating conditions where service experience is lacking. These will often behave differently than previous generations of systems.

Validations of structural designs, driven solely by lack of confidence in predicted response, are a costly and time consuming process. Overconservative designs are the only options available to counter unpredictable and potentially catastrophic performance.

Fracture mechanics must provide a general and unified framework to address this diversity of issues. The approach must be durable and emphasize accuracy, versatility and consistency. This can only be achieved by a fundamental quantitative understanding of the interrelation of material behavior, structural geometry and environment (mechanical, thermal and chemical); this requires the systematic interaction between theoretical concepts and active experimental observation. The goal is a rational synthesis algorithm for the analysis and design of material-structural systems.

ACKNOWLEDGMENT

The authors wish to thank Dr. Robert Badaliance for many stimulating discussions, helpful suggestions, encouragement and support.

REFERENCES

[1] Rice J.R. and Tracy, D.M., "On the Ductile Enlargement of Voids in Triaxial Stress Fields", *Journal of the Mechanics and Physics of Solids*, Vol. 17, pp. 201-217, 1969.

[2] Hutchinson, J.W. and Tvergaard, V., "Mechanics of Void Nucleation in Plastically Deforming Solids", Twentieth National Symposium on Fracture Mechanics, 1987.

[3] Griffith, A.A., "The Phenomena of Rupture and Flow in Solids", *Philosophical Transactions of the Royal Society*, Vol. 163, pp. 163-197, 1921.

[4] Irwin, G.R., "Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate", *Journal of Applied Mechanics*, Vol. 24, pp. 361-364, 1957.

[5] Sih, G.C., "A Special Theory of Crack Propagation", *Methods of Analysis and Solution of Cra ̈ Problems*, pp. 21-45, 1973.

[6] Rice, J.R., "A Path Independent Integral and the Approximate Analysis of Strain Concentrations by Notches and Cracks", *Journal of Applied Mechanics*, Vol. 35, pp. 379-386, 1968.

[7] Freudenthal, A.M., *The Inelastic Behavior of Engineering Materials and Structures*, 1950.

[8] Gillemot, L.F., "Criterion of Crack Initiation and Spreading", *Engineering Fracture Mechanics*, Vol. 8, pp. 239-253, 1976.

[9] Sih, G.C., "Prediction of Crack Growth Characteristics", Proceedings of *Symposium on Absorbed Specific Energy Strain Energy Density Criterion*, pp. 3 16, 1981.

[10] Matic, P. and Jolles, M.I., "Constitutive Theory, Damage Models and Three-Dimensional Fracture Mechanics Analyses", Nineteenth National Symposium on Fracture Mechanics, 1986.

[11] Matic, P., Kirby, G.C. and Jolles, M.I., "Aspects of Continuum Damage and Fracture", Twenty-third Annual Meeting of the Society of Engineering Science, 1986.

[12] Jolles, M.I., "Fracture Mechanics Methodologies", Aerospace Vehicle Technology Conference, 1986.

[13] Matic, P. and Jolles, M.I., "Defects, Constitutive Behavior and Continuum Toughness Considerations for Weld Integrity Analysis", NRL Memorandum Report 5935, 1987.

[14] Matic, P., Kirby, G.C. III and Jolles, M.I., "The Relationship of Tensile Specimen Size and Geometry Effects to Unique Parameters for Ductile Materials", NRL Memorandum Report 5936, 1987.

[15] Matic, P. and Jolles, M.I., "The Influence of Small Defects on Tensile Specimen Ductility and Symmetry of Deformation", NRL Memorandum Report 5937, 1987.

[16] Matic, P. and Jolles, M.I. "The Influence of Weld Metal Properties, Weld Geometry and Applied Load on Weld System Performance", NRL Memorandum Report 5987, 1988.

[17] Gensheimer, V.M., Matic, P. and Jolles, M.I., "Integrity Analysis of a T-Frame Stiffened Panel with a Flange Weld Defect", NRL Memorandum Report 5990, 1988.

[18] Gensheimer, V.M., Matic, P. and Jolles, M.I., "Welded Joint Integrity Analysis: Relative Criticality of Weld Defect and Remote Deformation", NRL Memorandum Report 6022, 1988.

Table 1 — Observed Fractographic Features of HY-100 Steel

Gage Length (in)	Gage Dia. (in)	Average MV Aspect Ratio	Linear MV Density (#/10 μm)	MVC Fraction	Ductile Tear Fraction	Cleavage Fraction
2.0	0.3	0.7656	2.39	0.8986	0.0613	0.0401
0.5	0.3	0.5710	2.21	0.7679	0.0911	0.1410
2.0	0.7	0.4244	2.01	0.5970	0.1472	0.2558
0.5	0.7	0.2266	1.79	0.4129	0.2008	0.3863

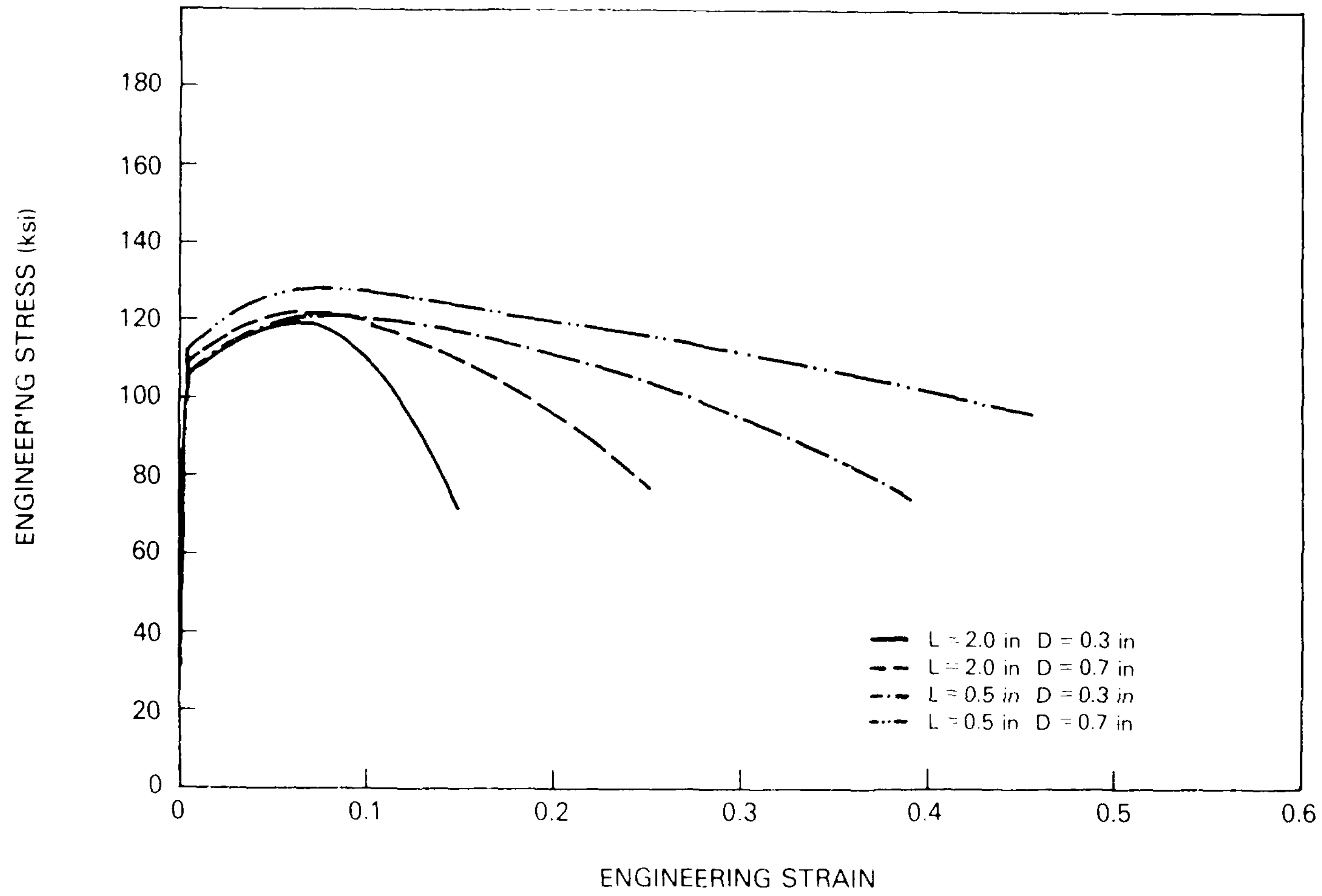


Fig. 1 Tensile specimen response for HY-100 steel.

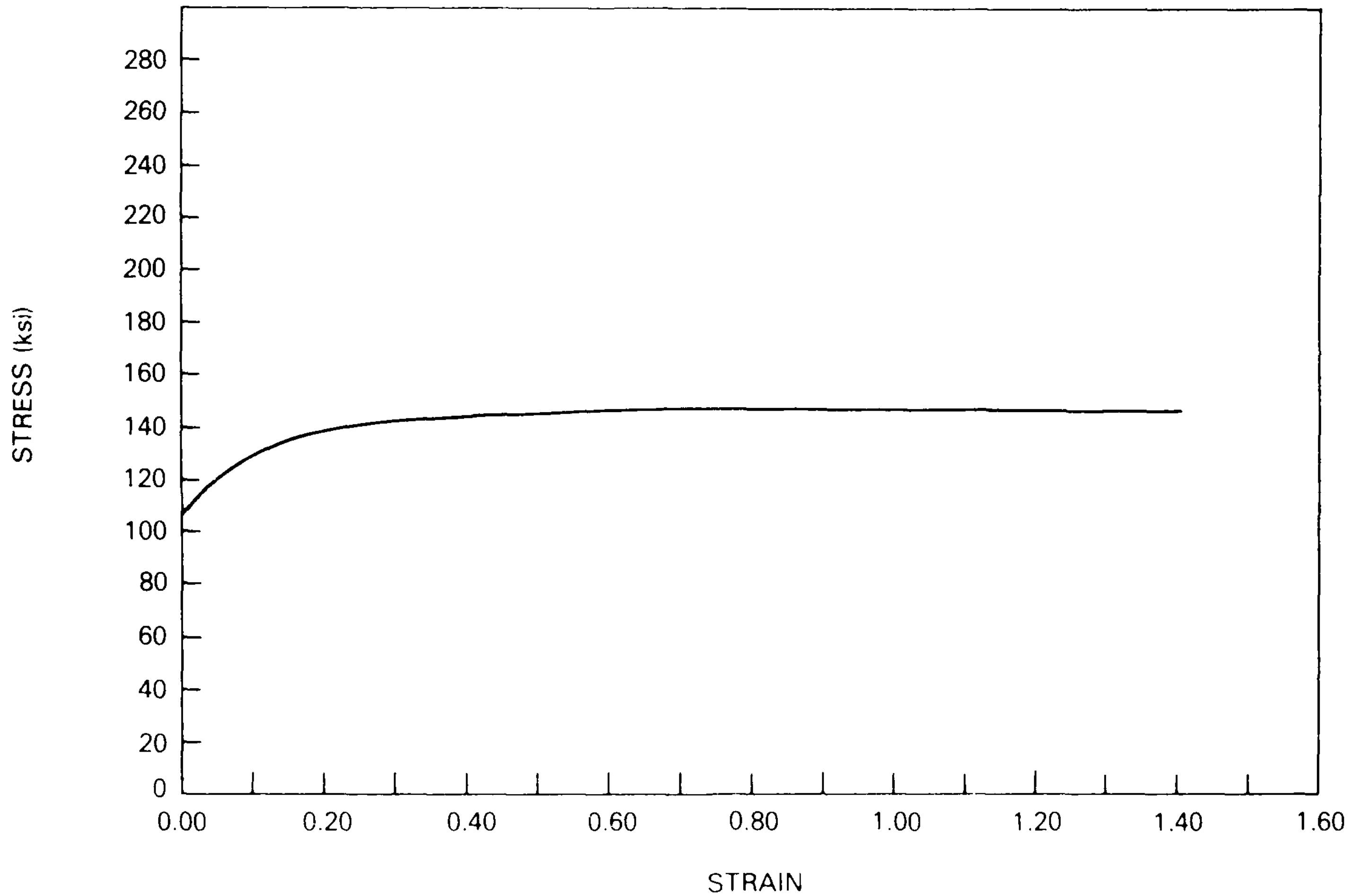


Fig. 2 Continuum stress-strain relation for HY-100 steel determined by hybrid computational experimental solution.

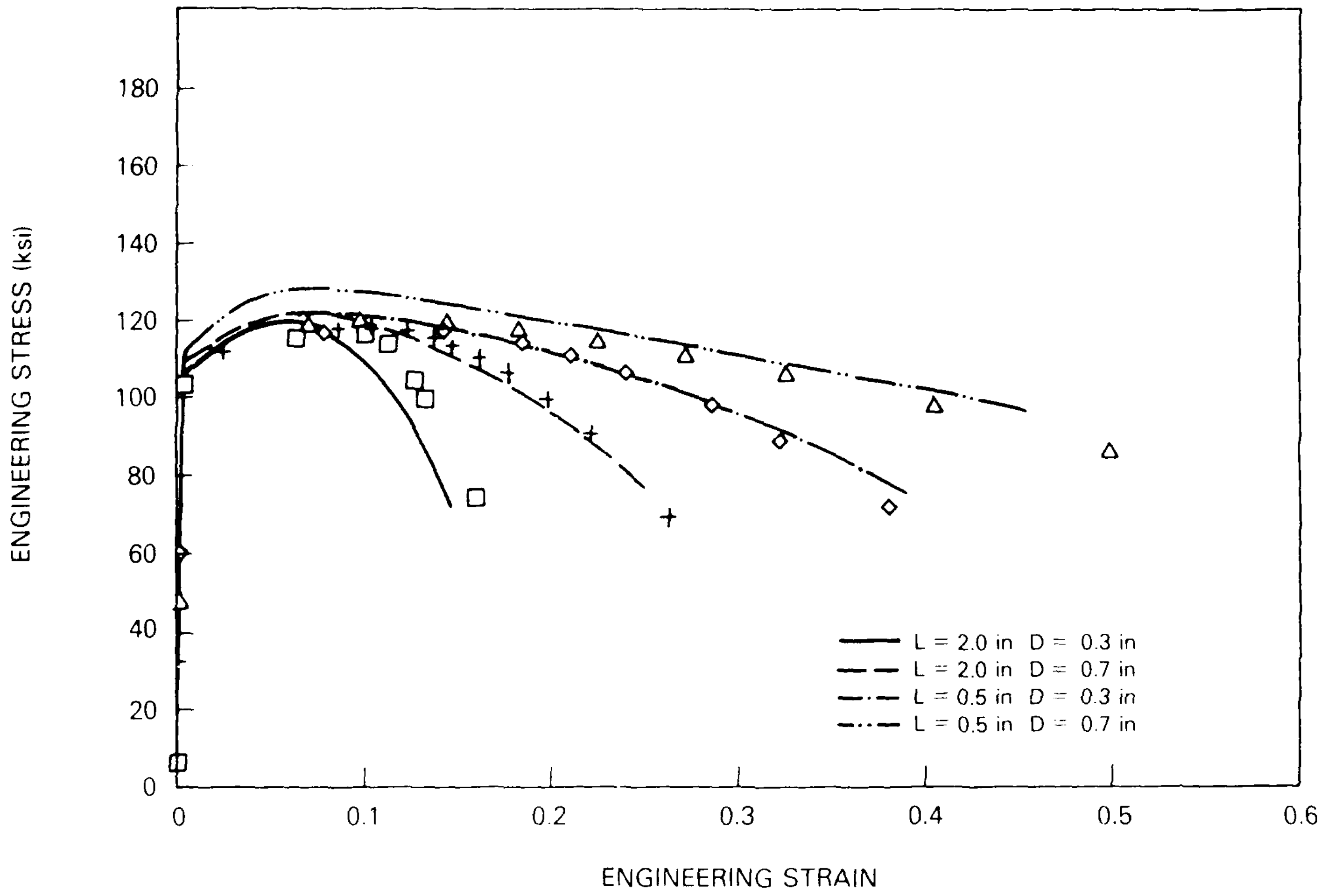
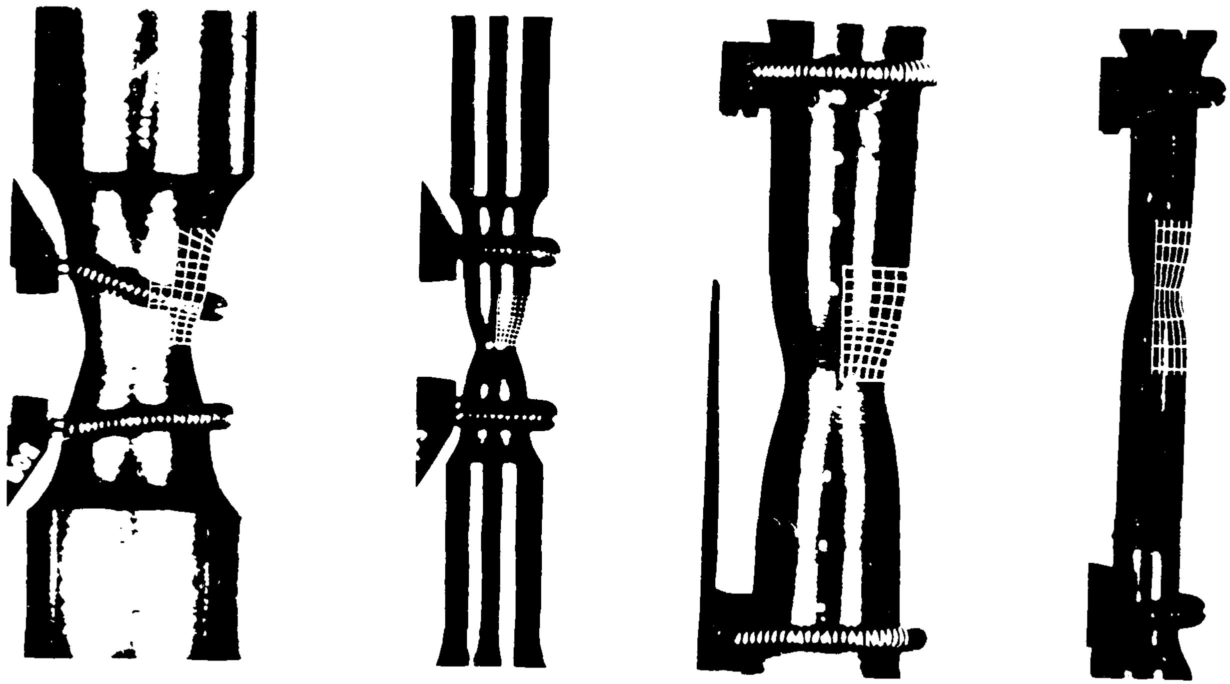
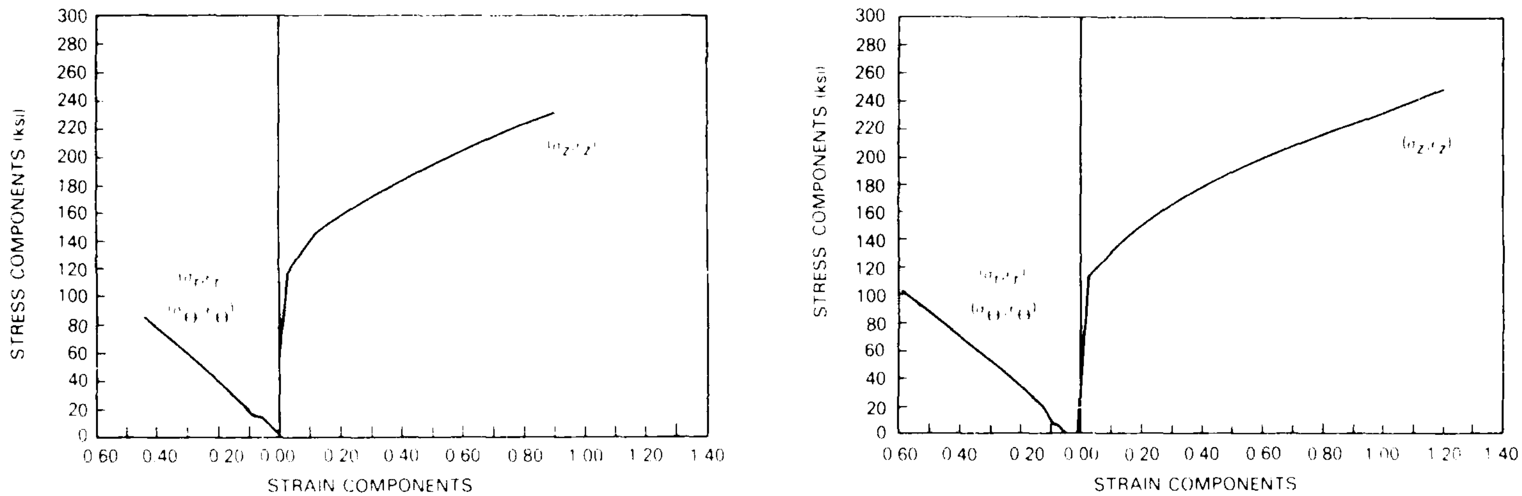


Fig. 3 Comparison of predicted and measured global deformation of tensile specimens of *HY-100* steel.



L/D = 0.71 1.67 2.86 6.67

Fig. 4 — Comparison of predicted and measured local necking deformation of tensile specimens of HY-100 steel.



(a)

(b)

Fig. 5 — Differences in the history of the triaxiality of the local deformation state at the center of 0.7″ diameter tensile specimens of HY-100 steel and resulting critical strain energy density. (a) 0.5″ gage length with w_c = 128.9 ksi (b) 2.0″ gage length with w_c = 174.3 ksi.

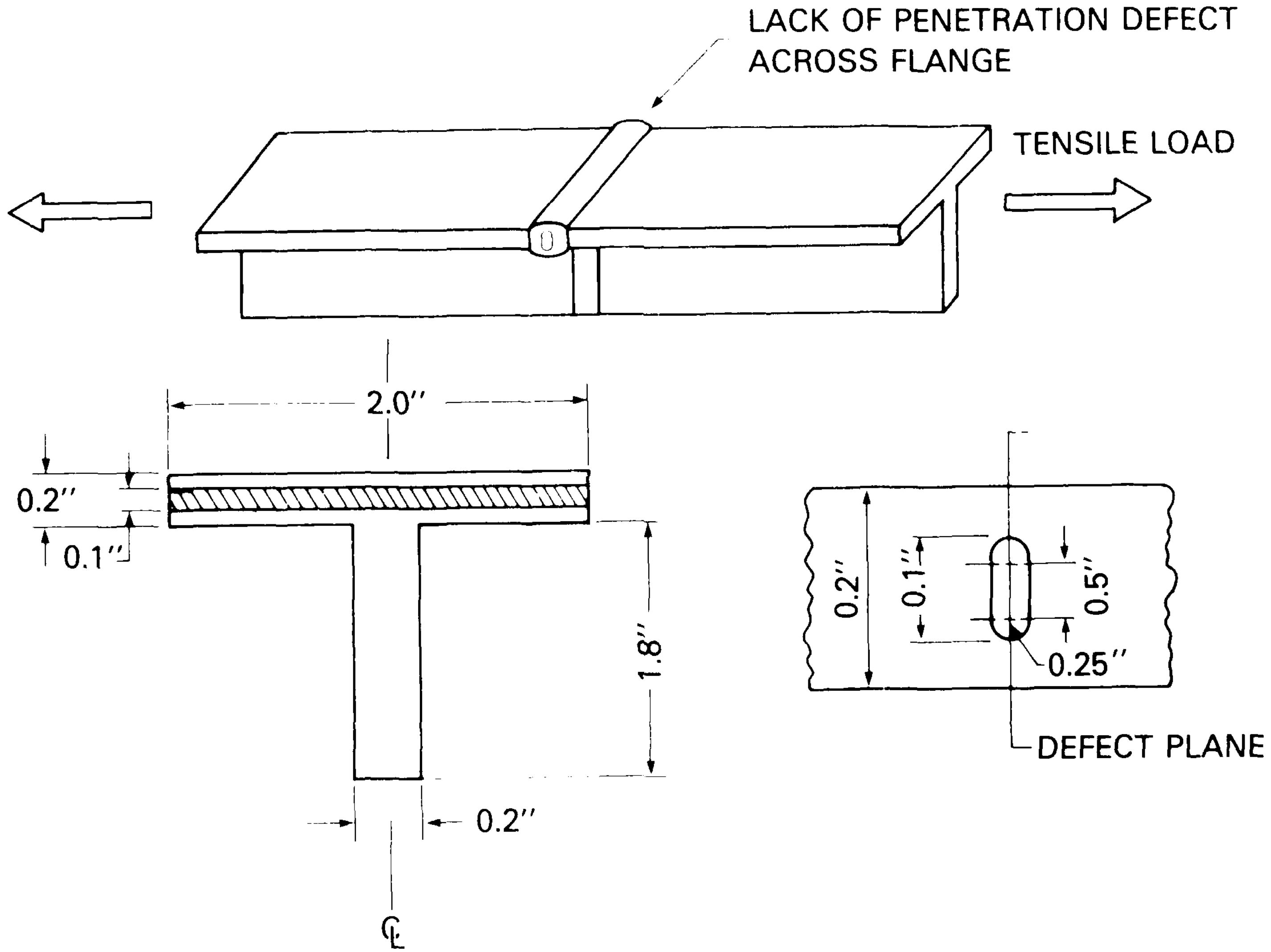


Fig. 6 — T-section containing a weld defect across the flange.

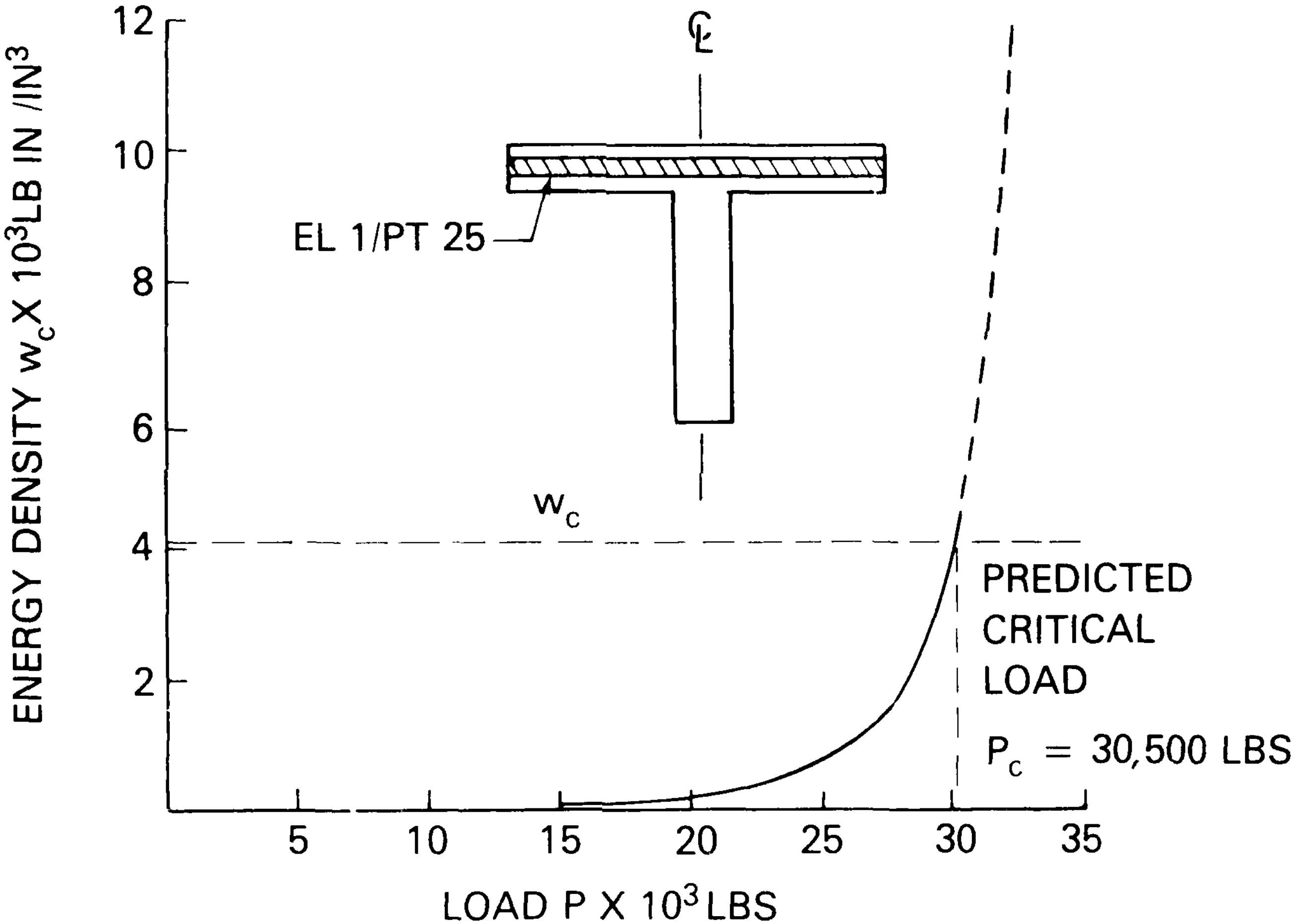


Fig. 7 — Strain energy density history at critical location determined by analysis.

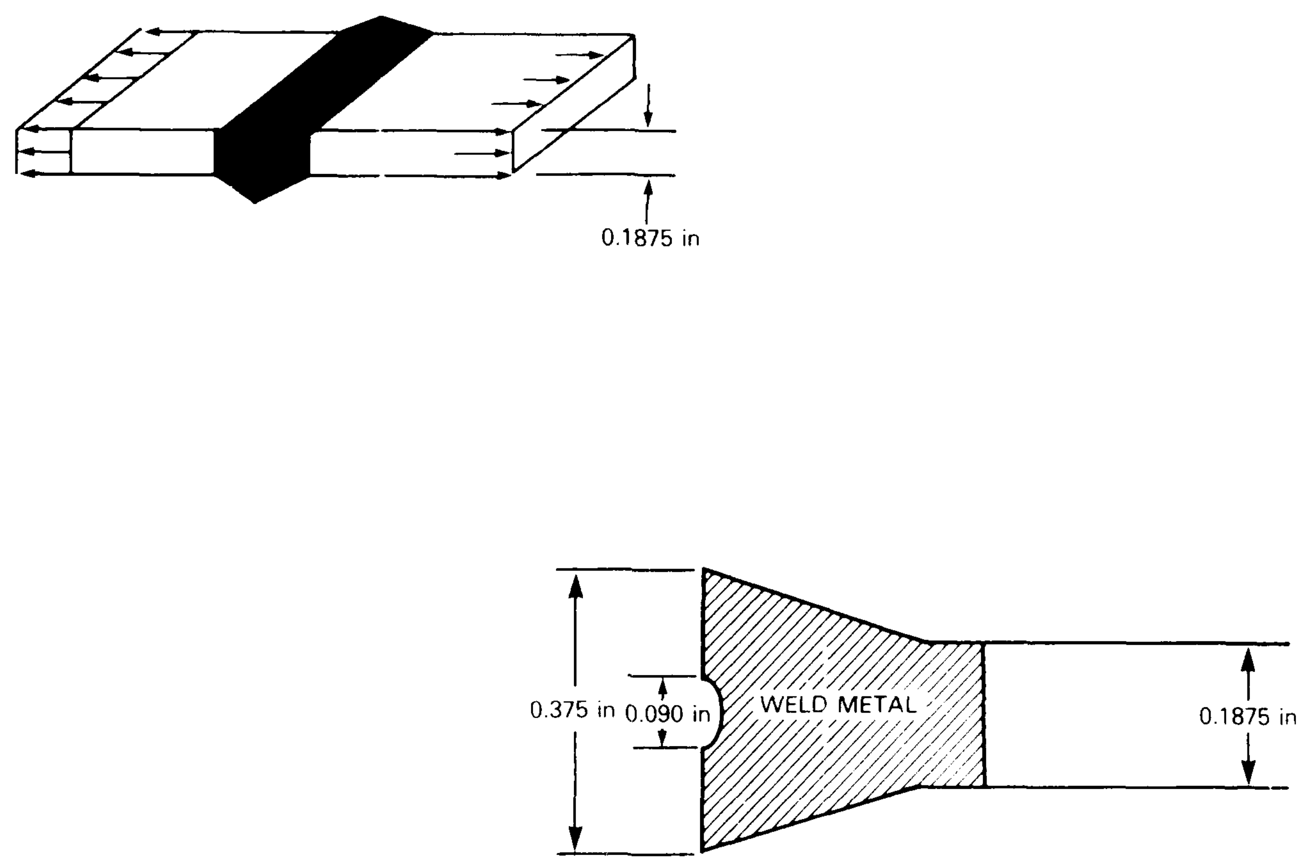


Fig. 8 — Plate containing a through thickness weld defect.

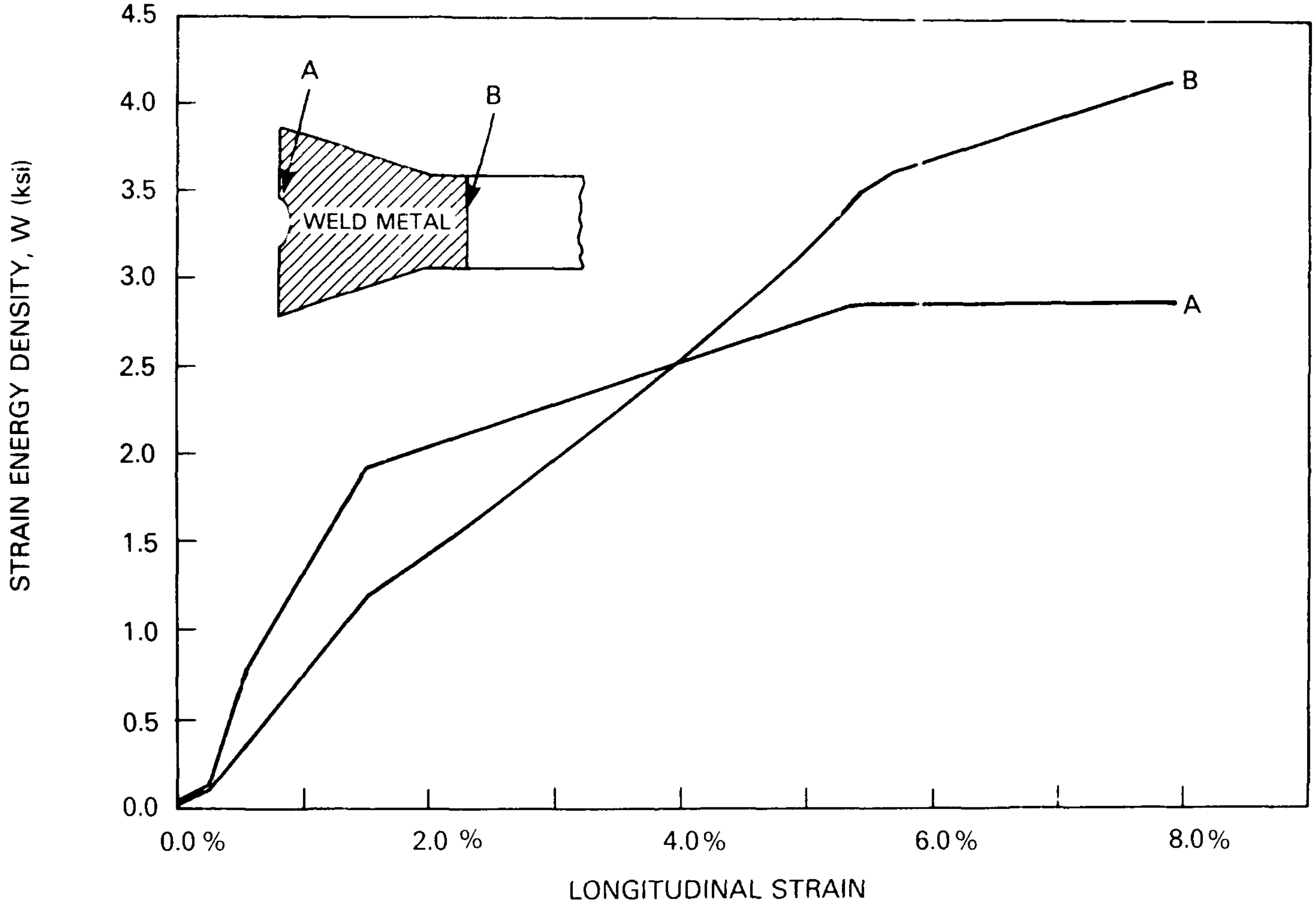
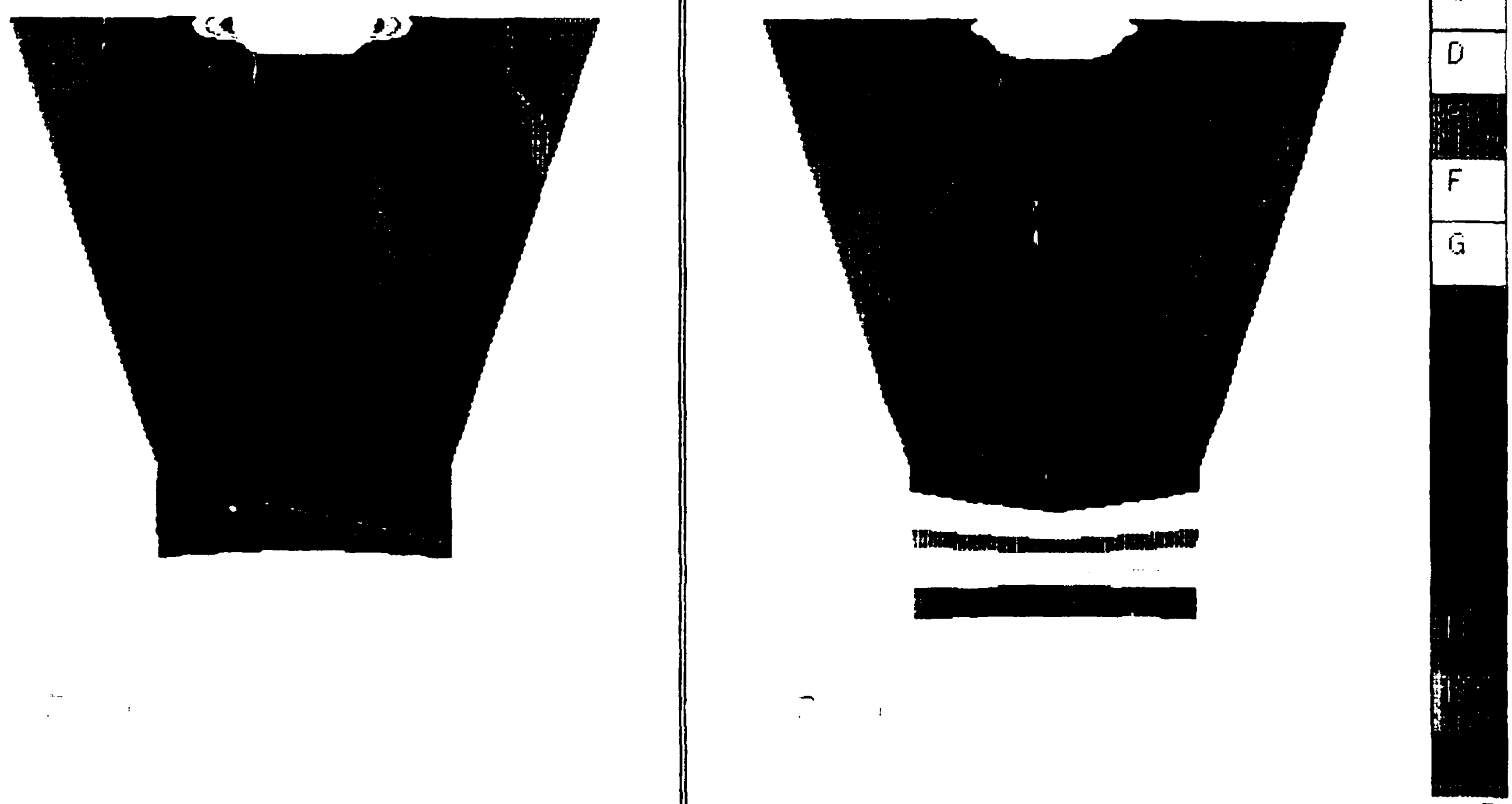


Fig. 9 — Strain energy density history at edge of defect and fusion line determined by analysis.

Fig. 10 – Load redistribution shifts concentration from edge of defect to fusion line as seen by relative strain energy density contours at load of (a) 1.5% strain (b) 7.8% strain. The scale is maximum (red) to minimum (black).



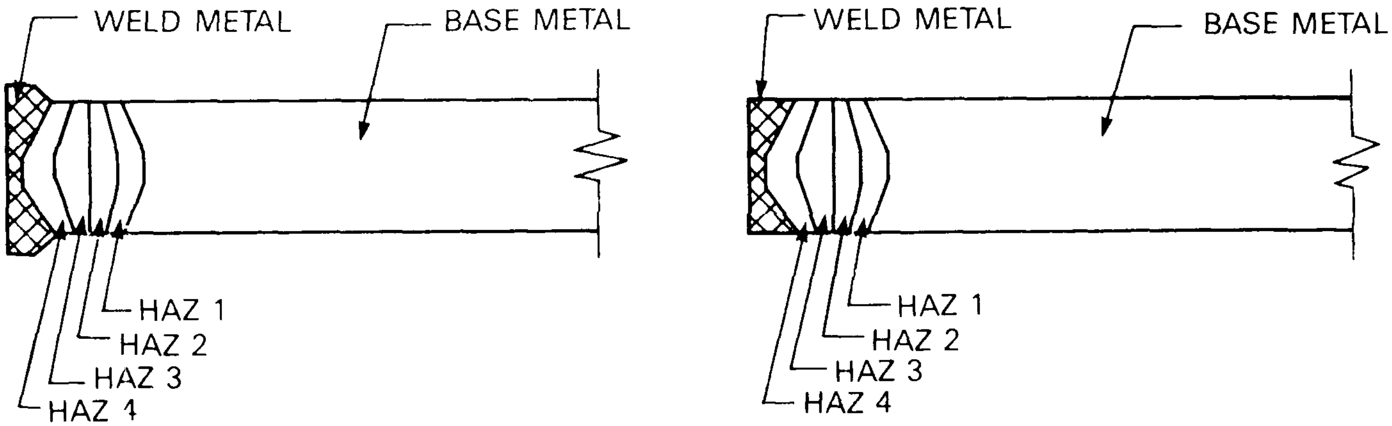


Fig. 11 — Material zones for welded plate (a) with weld crown (b) without weld crown.

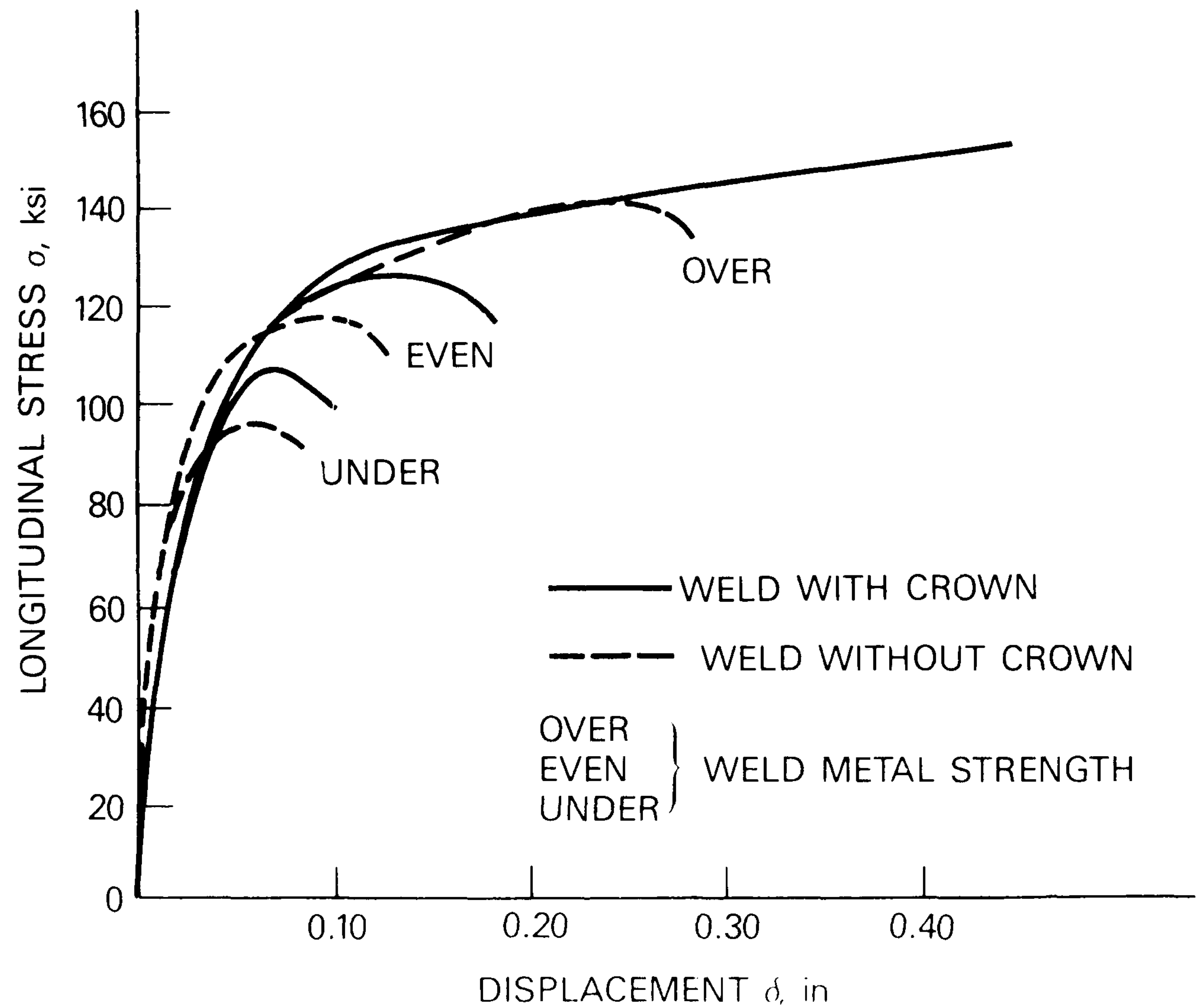


Fig. 12 Load versus displacement determined by analysis demonstrates affect of weld metal properties and presence of weld crown on weld system ductility.

DATE
FILMED
-8